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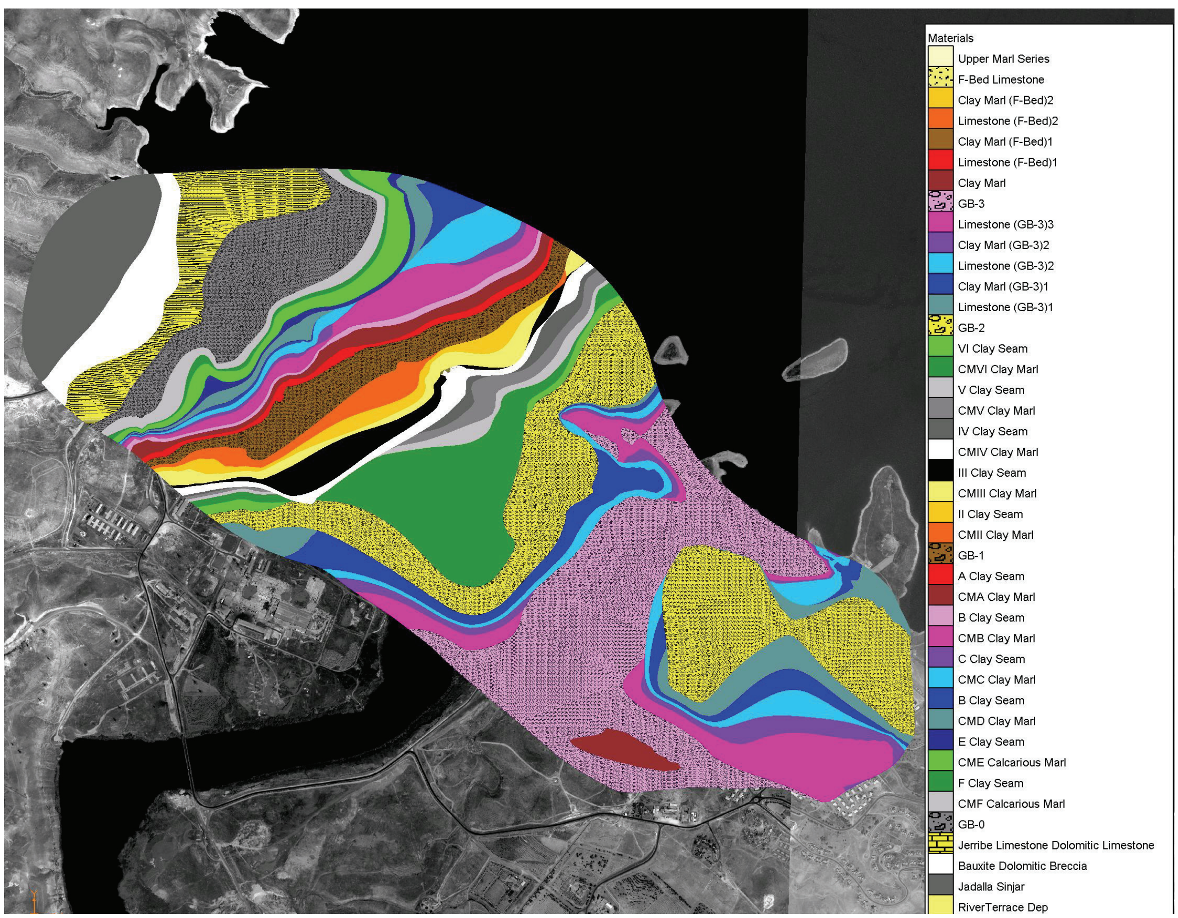
September 2007



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Final report

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Baghdad, Iraq

Abstract: Mosul Dam, Iraq, was built in the 1980s on a foundation of soluble geologic materials. Because of the solubility of its foundation and abutments, maintenance grouting began immediately after construction and continues to the present. The U.S. Army is concerned about the stability of the dam, and about the potential military and political impacts that would accompany dam failure. At the request of the U.S. Army Corps of Engineers' Gulf Region Division, the U.S. Army Engineer Research and Development Center (ERDC) developed a three-dimensional (3-D) geologic conceptual model of the dam, as a tool to assist with improving dam safety and updating grouting operations. To develop the model, the ERDC Project Delivery Team built a geographic information system based on recent imagery, coupled with paper maps and geologic cross sections from the 1980s with minimal and inconsistent positional accuracy. Historic geologic data were translated into digital files and georeferenced, then consolidated and refined into a consistent set of lithologic information that was entered into the U.S. Department of Defense Groundwater Modeling System (GMS), the U.S. Army's specialized tool for performing subsurface modeling studies.

Using the tools available in GMS, the ERDC team constructed a 3-D geologic model of the foundation and abutments comprising 43 unique geologic units. The 3-D nature of the model, along with the ability to rotate, view, and create cross sections, adds significantly to the understanding of the size, shape, and arrangement of rock units beneath Mosul Dam and the relevant processes that affect the safety of the dam and its foundation under operating conditions.

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Preface

This report documents development of a three-dimensional (3-D) geologic conceptual model of the area of Mosul Dam, Iraq, accomplished by the U.S. Army Engineer Research and Development Center (ERDC). The work was performed in accordance with a Memorandum of Agreement (MOA) for the U.S. Army Engineer Division, Gulf Region, entitled "Project and Contracting Office (GRD/PCO) to Provide Three-Dimensional Model Development in Support of the Mosul Dam Enhanced Grouting Program." The MOA was signed on 30 May 2006 by Dr. James R. Houston, Director, ERDC, and on 28 May 2006 by COL John S. Medeiros, SPCO Water Lead, Project and Contracting Office.

This was part of a study of Mosul Dam that included development of a 3-D geologic conceptual model and numerical groundwater model; technology transfer by way of workshops in September 2006 and April 2007; and updating of a previously developed analysis of potential failure modes of the dam. The work was performed during the period June 2006 to August 2007 by a multi-disciplinary team from the Geotechnical and Structures Laboratory (GSL), Coastal and Hydraulics Laboratory (CHL), and Environmental Laboratory (EL), ERDC, Vicksburg, MS.

The primary project partners for this effort were the ERDC and GRD/PCO. The Iraq Ministry of Water Resources and the science and engineering staff of Mosul Dam also are key stakeholders who are using the products resulting from this project.

Dr. Jeffrey Jorgeson, CHL, was program manager for the ERDC from the beginning of the project through January 2007, after which Dr. Mark Jourdan, CHL, was program manager for the ERDC. Along with the program managers, contributors to the overall effort of model development included (in alphabetical order): Seth W. Broadfoot (GSL), Earl V. Edris (CHL), Julie R. Kelley (GSL), Thomas E. McGill (GSL), Christian McGrath (EL), Dr. Monte L. Pearson (GSL contractor), Cary A. Talbot (CHL), Nalini Torres (GSL), Dr. Lillian D. Wakeley (GSL), and Dr. Robert M. Wallace (CHL). Broadfoot and Talbot built and populated the 3-D model. Dr. Wakeley, Kelley, Talbot, Dr. Pearson, and Broadfoot prepared this report.

The authors wish to thank COL Richard B. Jenkins for his input, interest, and encouragement during the performance of this project.

Work in GSL was performed under the direct supervision of Dr. Lillian D. Wakeley, former Chief, Engineering Geology and Geophysics Branch; Dr. Robert L. Hall, Chief, Geosciences and Structures Division; Dr. William P. Grogan, Deputy Director, GSL; and Dr. David W. Pittman, Director, GSL. In CHL, work was performed under the supervision of Edris, Chief of Hydrologic Systems Branch; Bruce A. Ebersole, Chief, Flood and Storm Protection Division; Dr. William D. Martin, Deputy Director, CHL; and Thomas W. Richardson, Director, CHL.

COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

Executive Summary

During the period June 2006 through July 2007, the U.S. Army Engineer Research and Development Center (ERDC) supported the Ministry of Water Resources of Iraq with geologic, hydrogeologic, and geotechnical issues of Mosul Dam through a Memorandum of Agreement with the U.S. Army Engineer Division, Gulf Region (GRD). The ERDC Mosul Dam Project Delivery Team (PDT) generated a three-dimensional (3-D) geologic conceptual model of the foundation and abutments of Mosul Dam, Iraq, including an area immediately surrounding the dam. The purpose of the model was to consolidate nondigital information into a single geo-visualization tool for use by the Mosul Dam staff as they transition to an Enhanced Grouting Program for dam safety. The geologic conceptual model became the basis for a hydrogeologic numerical flow model developed by the ERDC PDT and described in another report.

Most of the geologic data used to develop this tool were provided in the Mosul Dam Library of Documents (LOD) (Washington International/ Black and Veatch 2004), an unpublished 13-volume collection of engineering and geologic reports and illustrations. Most of the entries in the LOD were generated during the 1980s by various consultants performing site characterization and preconstruction activities, augmented by reports written by panels of experts over the past 20 years. As an intermediate step, the ERDC PDT built a project geographic information system (GIS) based on recent imagery coupled with paper maps and geologic cross sections from the 1980s that have minimal and inconsistent positional accuracy. The available data were consolidated and refined into a consistent set of lithologic information that was entered into the U.S. Department of Defense Groundwater Modeling System (GMS), the U.S. Army's specialized tool for performing subsurface modeling studies.

Using the tools available in GMS, a 3-D geologic model of the foundation and abutments was constructed comprising 43 unique geologic units defined by the ERDC PDT and based on 1980s data. The 3-D nature of the model along with the ability to rotate, view, and create cross sections of the model significantly add to the understanding of the size, shape, and arrangement of rock units beneath Mosul Dam and the relevant processes

that affect the safety of the dam and its foundation under operating conditions.

The ERDC PDT transitioned these tools to the Mosul Dam staff through a hands-on workshop (April 2007) that included a summary of the regional and site-specific geologic setting and its engineering implications. During the workshop, Mosul Dam staff members received copies of the GIS, the geologic conceptual model, and the hydrogeologic model, accompanied by hands-on instruction in using these 3-D numerical tools. This highly successful coupling of a hydrogeologic conceptual model and 3-D groundwater flow model of the Mosul Dam foundation and abutments represents a unique and novel approach to management of a problem dam and is among the most detailed geologic conceptual models ever built using the GMS platform.

1 Purpose and Scope

This report describes the process of translating historical paper information about the geology of a high-risk dam into a three-dimensional (3-D) software-based conceptual geologic model. The conceptual model consolidates data that previously could be viewed only as individual pieces of paper or as portable document format (pdf) files. With the 3-D model, each piece of the total geologic puzzle can be displayed and visualized in relation to any or all of the other pieces. The purpose of the 3-D tool is to provide a holistic picture of conditions under the dam relative to rock type, unit thickness and distribution, and geologic structures. For example, critical features such as near-horizontal bedding can cause preferred groundwater flow, and focus the directional movement of dissolution. The georeferenced geologic information and visualization options of the 3-D model will facilitate future maintenance grouting and operation of the dam. The purpose of this report is to describe ERDC activities to develop the conceptual model and transition it to the Mosul Dam staff.

2 Background

Mosul Dam (formerly known as Saddam Dam) was constructed in the 1980s on the Tigris River near the city of Mosul, Iraq, for irrigation, flood control, water supply, and hydropower. The site was chosen for reasons other than geologic or engineering merit. From a geologic standpoint, the foundation is very poor, and the site geology is the principal cause of continuing intense concern about the safety of the structure. Specifically, the dam was constructed on alternating and highly variable units of gypsum, anhydrite, marl, and limestone, each of which is soluble in water under certain conditions.

Impoundment of a large freshwater reservoir in contact with these unstable geologic materials promotes continuous dissolution in the foundation and abutments, with preferential and rapid dissolution of gypsum and anhydrite layers. This condition creates a situation demanding extraordinary engineering measures to maintain the structural integrity and operating capability of the dam. The requisite engineering measures have included maintenance grouting of the structure continuously since construction. The purpose of maintenance grouting is to close water-flow pathways that open by rapid dissolution of geologic materials in the foundation and abutments. The consensus among various expert panels and engineers and scientists who have studied or worked directly on Mosul Dam is that the embankment was constructed well and is not the cause for concern. However, without continuous maintenance grouting of the foundation and abutments, the dam would fail.

The U.S. Army Engineer Division, Gulf Region (GRD), became increasingly concerned about the safety of the dam as their tenure in-country lengthened. An international panel of experts (IPE) had recommended that the structural integrity of Mosul Dam could be improved by transitioning the grouting program from 1980s practices to the best available 21st-century techniques and equipment. Further, the IPE recommended that a 3-D geologic model and hydrogeologic or groundwater flow model should be developed to support the transition to enhanced grouting.

The ERDC Mosul Dam Project Delivery Team (PDT) was formed as an interdisciplinary working group under a Memorandum of Agreement (MOA) between ERDC and GRD in May 2006. The principal goal of the team was to develop a conceptual geologic model and groundwater model of Mosul Dam that would

- Provide a 3-D visualization tool to enable geologists and engineers on the Mosul Dam staff to make best use of previously unusable or minimally usable data
- Establish the basis for data files with positional accuracy for future dam operations and maintenance
- Provide to the Mosul Dam staff a geologic tool that can be used into the future to evaluate the performance of ongoing and future grouting and monitoring programs
- Improve understanding of the foundation and reservoir geology, geochemistry, and hydrogeology
- Improve understanding of the effects of grouting on the foundation's ability to withstand further dissolution
- Improve understanding of how and why sinkholes and other dissolution features are forming
- Provide the geologic data for the software that will support and operate the Enhanced Grouting Program.

To accomplish these purposes, the ERDC PDT for model development included expertise in geology, geochemistry, geological engineering, geographic information systems (GIS), hydraulic engineering and hydrology, and numerical groundwater modeling, with team members from ERDC Coastal and Hydraulics, Geotechnical and Structures, and Environmental Laboratories, as well as outside consultants. This report describes development of the 3-D conceptual geologic model that was the basis of the numerical groundwater model and was supporting technical information for an update of potential failure-mode analysis described in a separate document.

3 Approach

A ***geologic conceptual model*** is the mental picture of what is in the subsurface or how a surface or subsurface feature formed, based upon available information. As more data are acquired, one modifies and refines a mental picture and uses visual images such as cross sections, maps, and 3-D visualization. The quality of a conceptual model depends partly on the quality and quantity of data and partly on the ability of the project team to interpret those data and present them in a way that enhances communication and understanding. The aim is to understand factors that contribute to current and future conditions at the dam, and to explain the causes of geologic features and geotechnical phenomena to others. For a geologic study associated with a large engineering project such as Mosul Dam, the geologic setting is critically important not for its own sake, but for its engineering implications. Thus, the 3-D conceptual model is a tool to use in engineering and operational decisions about the dam.

The steps taken by the ERDC PDT to develop the geologic conceptual model included (1) data review and understanding of regional and local geology; (2) development of a GIS; (3) refining, interpolating, and interpreting the limited available data to derive a 3-dimensional conceptual model with advanced capabilities for visualization; and (4) entering available data into appropriate software. The ERDC PDT did not visit the Mosul Dam site.

Data review and regional geology

The primary source of information for the ERDC project was a 13-volume compilation of data and information on Mosul Dam spanning its construction and 20 years of operation, known as the Mosul Dam Library of Documents (LOD) (Washington International/Black and Veatch 2004, augmented in 2005). Based on information provided by GRD in the MOA, the ERDC team expected the LOD to include most of the geologic data necessary to form the basis of the conceptual model. The ERDC scope of work had been written with the understanding that the model would be based on the pre-existing LOD information, without benefit of new field studies. Because the LOD was provided to the ERDC on CDs, the team anticipated that there would be some exportable data sets with adequate positional accuracy to be incorporated into a GIS.

Review of most documents in the LOD revealed that the LOD had been generated by scanning paper documents of varying physical quality. While the LOD contained enough geologic information to define a conceptual picture of the regional geology, most of the data predated widespread use of GIS technology. The LOD included no exportable data files (such as Excel or other spreadsheets), and none of the information, such as descriptive logs from geological borings, was accompanied by numerical location information. This lack of exportable or positional data greatly complicated the process of generating a GIS and a 3-D conceptual model.

During a workshop that was held in Vicksburg, MS, USA, in September 2006, the ERDC PDT received some recent (2005 and 2006) spreadsheets and data in other formats directly from Mosul Dam staff. The files, including data from monitoring water chemistry and piezometer readings in 2005 and part of 2006, were valuable in understanding current conditions at the dam. Figures and interpretations derived from these data sets were presented at the Technology Transfer Workshop in April 2007 and included in other reports. Piezometer data were incorporated into the model and GIS. Also, a team from GRD visited the dam site in December 2006 and provided new digital photos, descriptions of current visible conditions, and rock samples from recent cores drilled in the east (left) abutment. The ERDC team used the photos and rock samples to cross-check interpretations of older data.

An additional component of the data review was locating and analyzing the usefulness of data from other sources, including open literature. Professional publications on such topics as sinkholes in evaporite rocks, gypsum karstification in the Mosul area, and the influence of Mosul Dam on sediment transport and geomorphic processes in the Euphrates-Tigris Basin all contributed to the conceptual geologic model of the region. A partial list of publications used for background information appears at the end of this report (References and Additional Data Sources).

Geographic Information System

A geographic information system is essential for managing the quantity of geographic, geologic, and geotechnical data involved in developing 3-D conceptual and numerical models. The GIS group of the ERDC PDT combined skills in remote sensing, engineering geology, hydrogeology, information management, 3-D visualization, and groundwater modeling. Two members of the PDT had previously deployed to Iraq as GIS

specialists. Initial digital data sets for the GIS came from military sources, other federal agencies such as the USGS, and from commercial sources.

Using commercially available software from ESRI, Inc., the GIS group constructed layers from digital aerial photographs and other imagery, providing fixed points to which other data sets could be matched or rectified. Surface topography, drainage patterns, and other features were available digitally. Figures 1 and 2 show two images of the dam, from different imagery sources and at different reservoir-pool levels. The team added layers for rock and soil types, geologic structural features, locations of piezometers (Figure 3), locations of sink holes, and other critical information. Developing the GIS was accomplished by a combination of interpretation of imagery and creation of new files by digitizing and rectifying paper printouts from the LOD and the Mosul Dam staff.

Refining, interpolating, and interpreting geologic data

Once the base layers of imagery were established, subsurface features such as faults, geologic strata variances as documented at the time of construction, dam-foundation features, etc., were added to form the third dimension (subsurface). Existing paper cross sections were digitized and rectified, such that their relationships to each other could be established. However, different cross sections and borehole logs had been prepared by different groups, with somewhat inconsistent assumptions and definitions of stratigraphy. Anomalies appeared at intersections of some cross sections and other drawings. The ERDC PDT used best geologic judgment based on the regional geologic setting, and advanced software options, to resolve discrepancies and anomalies in the geologic data.

Because of the lack of positional accuracy of geologic cross sections and boring logs, addition of the subsurface component also required best-guesses about position. The broad lines and large dots shown on nondigital drawings and maps were converted to GIS coordinates based on the center-line or center-point of mapped features. The actual size of a large dot on a map could be up to 100 m in diameter. Therefore, positional accuracy of the GIS and the 3-D conceptual model is approximately 100 m.

Software used for the conceptual model

Building on the data review and the digital data developed by the GIS team, a 3-D representation of the geologic conceptual model was

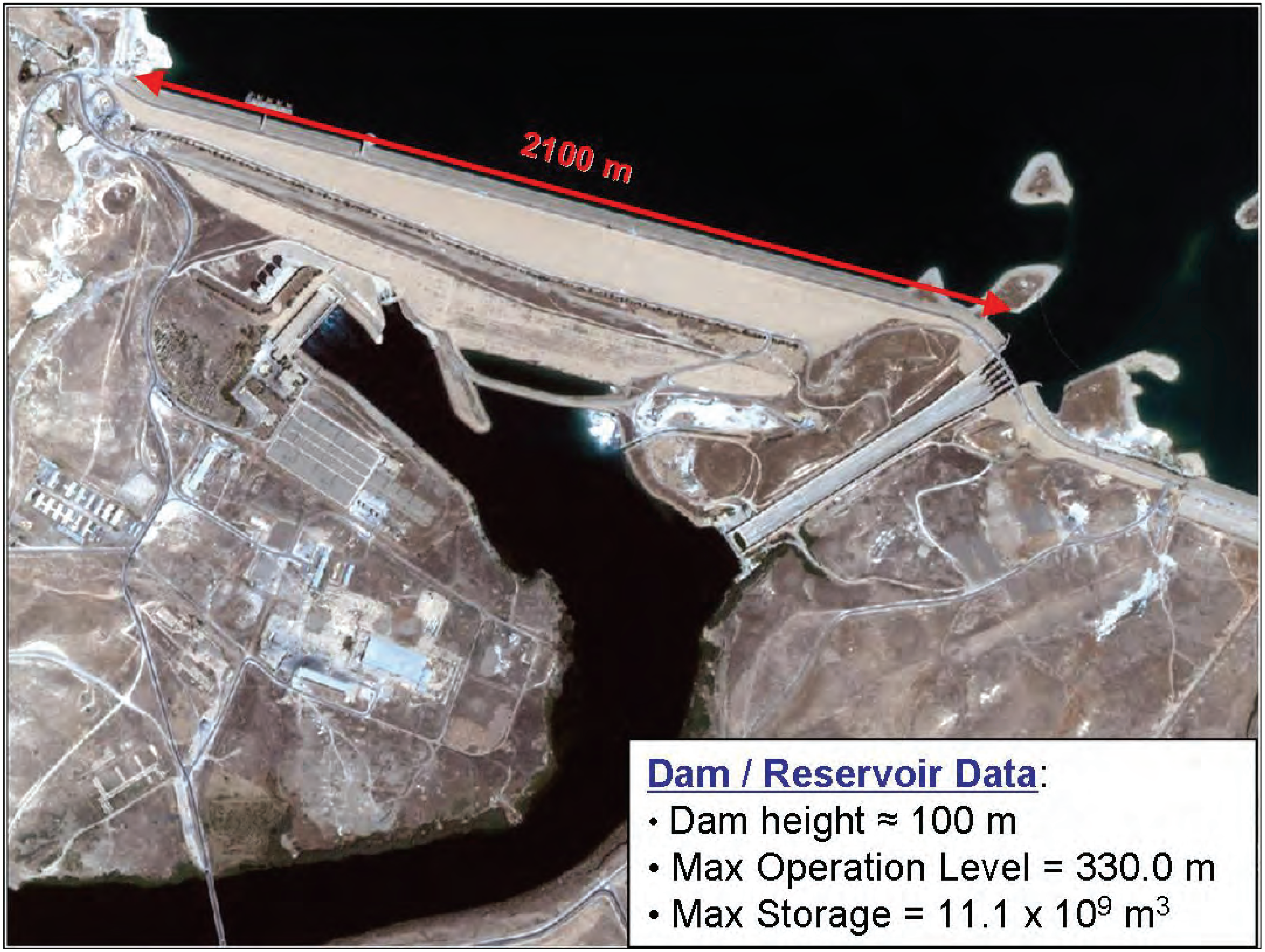

Figure 1. Image of Mosul Dam at high water, showing main spillway and downstream features.

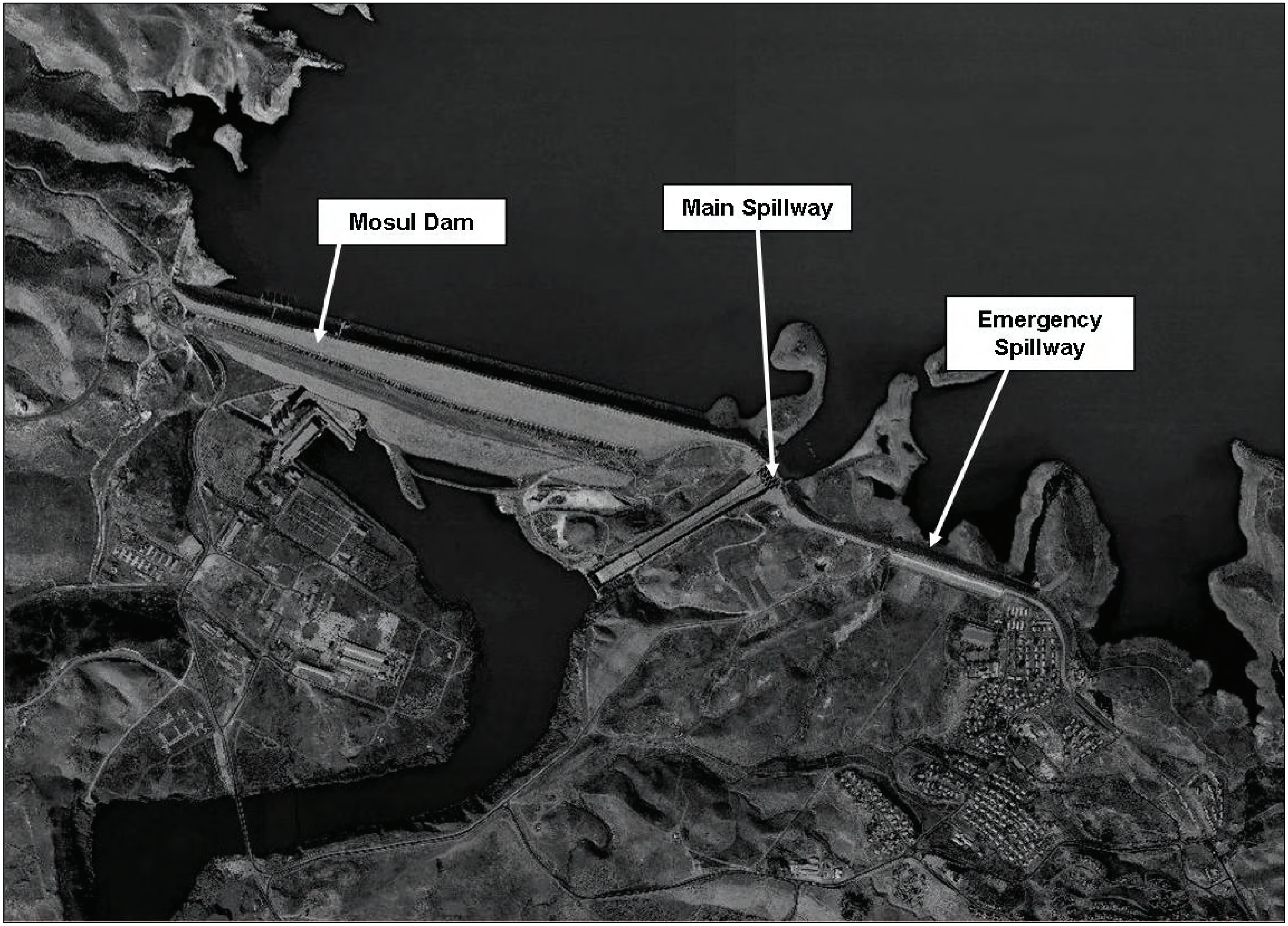

Figure 2. Image of Mosul Dam at lower reservoir level, showing area from residential village on the east to hills on the west (right) abutment.

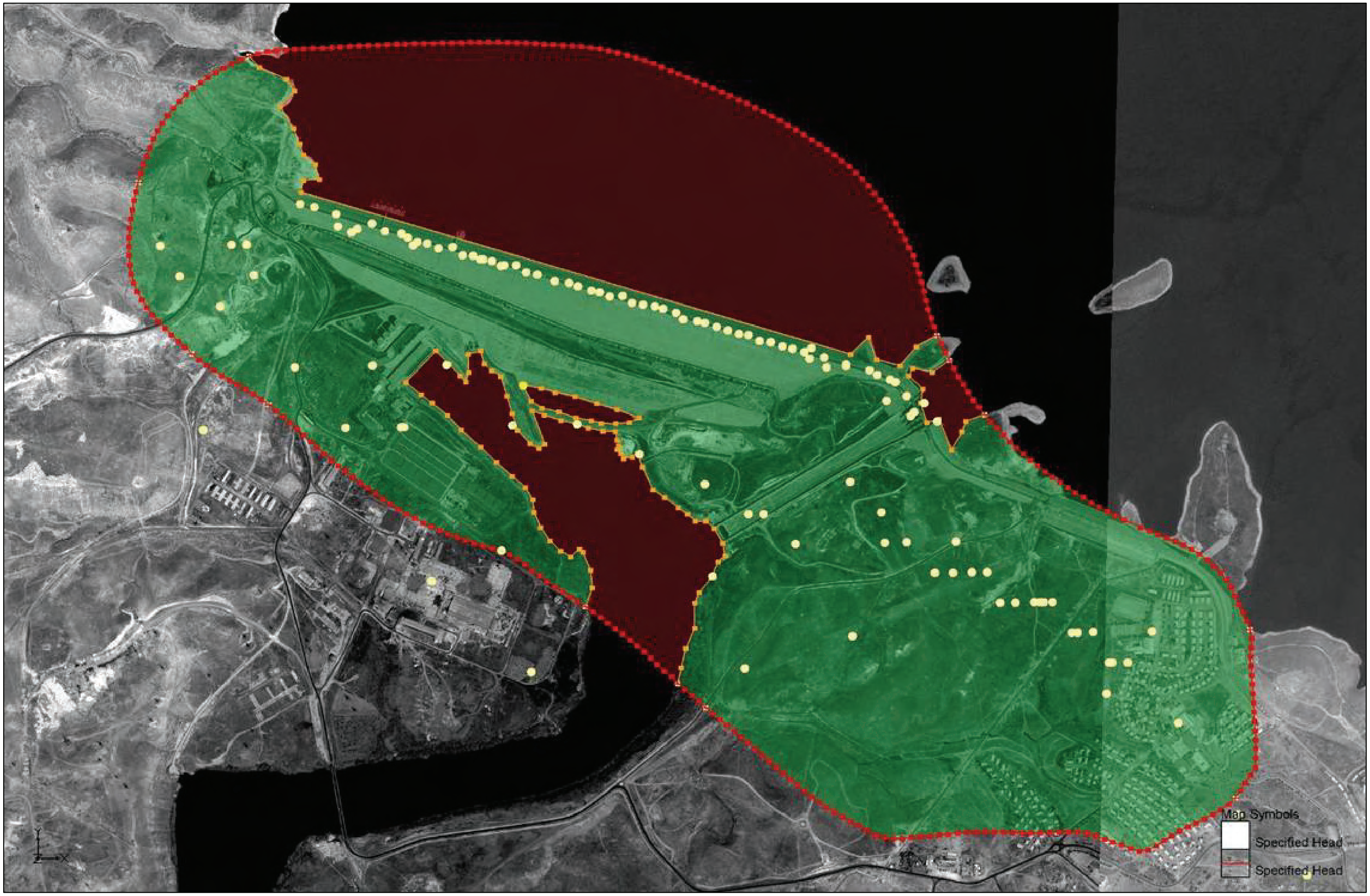

Figure 3. Image with footprint of geologic conceptual model shown by red dots. (Model area is shown in red over water and in green on land. Yellow dots are locations of piezometers.)

developed by members of the ERDC PDT using the Department of Defense Groundwater Modeling System (GMS). GMS is a tool developed by ERDC and other federal government partners to, among many other uses, provide a platform for the construction of geologic conceptual models. To accomplish this task, various types of 2-D and 3-D data are brought together and used to build a digital 3-D model that is consistent with the geologic conceptual model for a given site. Tools are provided for entering borehole and digital cross-section data, linking with GIS and other spatial data sources, and for constructing the 3-D geologic model layers according to geologic depositional principles. The resulting digital 3-D model can be used for geologic analysis, visualization, and calculation. In this case, it also can and was used as the basis for a 3-D computational model of groundwater flow. Owen et al. (1996) describe the capabilities of GMS. Jones et al. (2002), and Lemon and Jones (2003) describe other projects that use borehole logs and user-defined cross sections to develop solid models of subsurface stratigraphy in GMS, as was done for Mosul Dam.

In summary, the ERDC team built a 3-D model of the Mosul Dam site and surrounding area using the data sources identified in the LOD review and refined through the process described above, data provided during the data-exchange workshop in September 2006, data provided in subsequent email communication, and the GIS data layers developed by the GIS team. The team also used geologic judgment consistent with the overall geologic conceptual model. This model allowed the PDT to understand what interpretations of hydrogeology were possible and consistent with documented geologic history of the area. This model was also used as the basis for the follow-on 3-D numerical model that was developed for the Mosul Dam staff to simulate the groundwater flow conditions at Mosul Dam.

4 Data Used for the Model

The Library of Documents included a geologic map showing where the various geologic units at the Mosul Dam site were exposed at the surface at the time of construction, and indicating dip of the beds at various locations to indicate structural features in the subsurface. This map focused largely on the Butmah Anticline, the dominant structural feature of the west (right) abutment of the dam, where rock units dip steeply upstream and downstream and away from the axis of the anticline. However, the map also included all of the area subsequently covered by the footprint of the dam and its main spillway, as well as upstream areas now covered by water and downstream areas, including known sinkholes.

In developing the Geologic Conceptual Model, the ERDC PDT obtained detailed digital elevation data for the area surrounding the dam site. However, all available digital sources were from sampling events after the reservoir was filled, and therefore did not include the reservoir bathymetry. To construct lithology correctly upstream of the dam, it was necessary to know the bathymetry of the reservoir. Using available terrain contour maps of the prereservoir conditions, the team estimated reservoir bathymetry and created a new digital elevation model (DEM) that defines the top surface of the geologic conceptual model. Figure 4 shows examples of hyperspectral imagery and a DEM.

The ERDC PDT georeferenced the paper geologic map onto a recent QuickBird™ image of the area around the dam. This established spatial orientation for geologic structures and for cross sections that had been hand-drawn in 1984 as part of an initial hydrogeologic study (documented in Vol 13, LOD).

From the LOD, six cross sections and the geologic logs from four boreholes (out of a total of approximately 20 borehole logs) had positional information adequate for use in the initial 3-D model. The positional information consisted of chainage related to locations along the dam. During the Data Exchange Workshop in September 2006, Mosul Dam staff provided borehole logs for five additional boreholes (surrounding a sinkhole near the main spillway), for a total of nine borehole logs on the east (left) abutment. They also provided six additional cross sections that

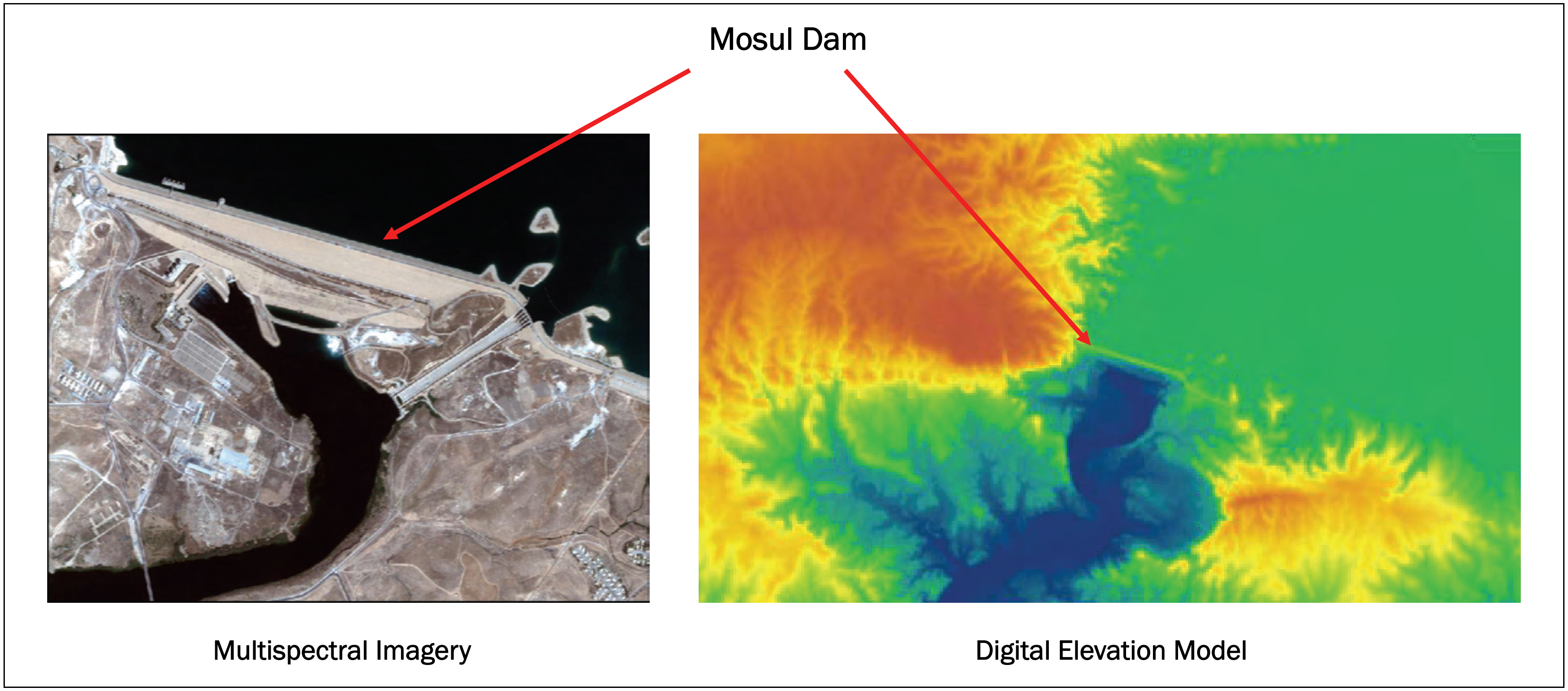

Figure 4. Image of Mosul Dam shown from multispectral imagery (left box) and as a digital elevation model (DEM, right box) at different scales. (On the DEM, elevation goes from higher to lower as color changes from orange to blue.)

could be located (within 100 m or less of actual location) on digital imagery. The input cross sections and borehole logs are included on the CD of this report.

The GMS software accommodates input from boreholes, that is, data for vertical columns of geologic information at a specific point location. The cross sections that had been generated in the 1980s had been based on borehole logs at the time they were drawn. But the original logs used to generate the original cross sections were not included in the LOD. To be able to enter geologic data into the software, the team generated borehole-equivalents (hereafter called generated boreholes) after creating digitized files from the (originally hand-drawn) cross sections. The generated boreholes are not invented, but are defined from panels of geologic information represented by the hand-drawn cross sections of the 1980s. Generated boreholes could be derived at any location along a cross section.

Once the locations and orientations of cross sections were fixed, they were translated into a usable format at the same scale as other data, by way of generated boreholes. The locations of the generated boreholes and the geologic data associated with them were entered into the GIS as an intermediate step in creating the 3-D model.

For the geologic conceptual model to be useful as a basis for a numerical hydrogeologic model, it had to include data for permeability of the geologic units. The only direct permeability data available to the ERDC PDT was a summary of measured permeability values corresponding to stratigraphic units combined into nine groups of decreasing permeability during the 1984 study and represented on six cross sections (Vol 13, LOD; reproduced here in Figure 5). Although original data had been color-coded to the hand-drawn cross sections, all files copied into the LOD were black-and-white. However, the nine generalized stratigraphic units, as represented along cross-section panels by generated boreholes, were adequate to generate the third (subsurface) dimension in GMS as a first draft of the model. Figure 6 shows intersecting cross sections from the first draft of the nine-layer model. Major modification to achieve the required level of geologic detail is described in Chapter 5, Geologic Complexity.

The outline or footprint of the model was defined by the extent of usable cross sections, and has a map area of 5.3 sq km. It includes the dam and

- Upper Marl Series
- F-bed limestone
- Lower Marl Series (
  - (- 5 beds of limestone
  - (- gypsum/anhydrite
  - (- undifferentiated marls corresponding to the "clayey series"
  - (- "chalky series"
  - (- G B O
- Jeribe limestone
- Bauxite (?)
- Jaddala/Sinjar

Number	Colour	K-values (m/s)	Geological formation
1		10^{-2}	F-bed limestone
2		10^{-3}	Overburden, exposed chalky series, exposed jeribe limestone
3		2.10^{-5}	Chalky series
4		4.10^{-6}	Exposed clayey series
5A		10^{-4} P 10^{-5} V	Jaddala/Sinjar
6		10^{-8}	Buaxite below 270 m a.s.l.
7A		5.10^{-7} V 5.10^{-6} P	Jeribe limestone
8A		5.10^{-8} V 5.10^{-6} P	Clayey series (marl-gypsum beds)
9A		10^{-8} V 10^{-6} P	Upper marl series
10		10^{-11}	Dam
11		10^{-9}	Grouted section

V: Vertical to layering

P: Parallel to layering

TAB.1: PERMEABILITY VALUES USED IN THE HYDROGEOLOGICAL MODEL

Figure 5. Simplified nine-unit stratigraphy with permeability (K) values, used in 1984 hydrogeologic study. (Reproduced from Mosul Dam Library of Documents, Vol 13.)

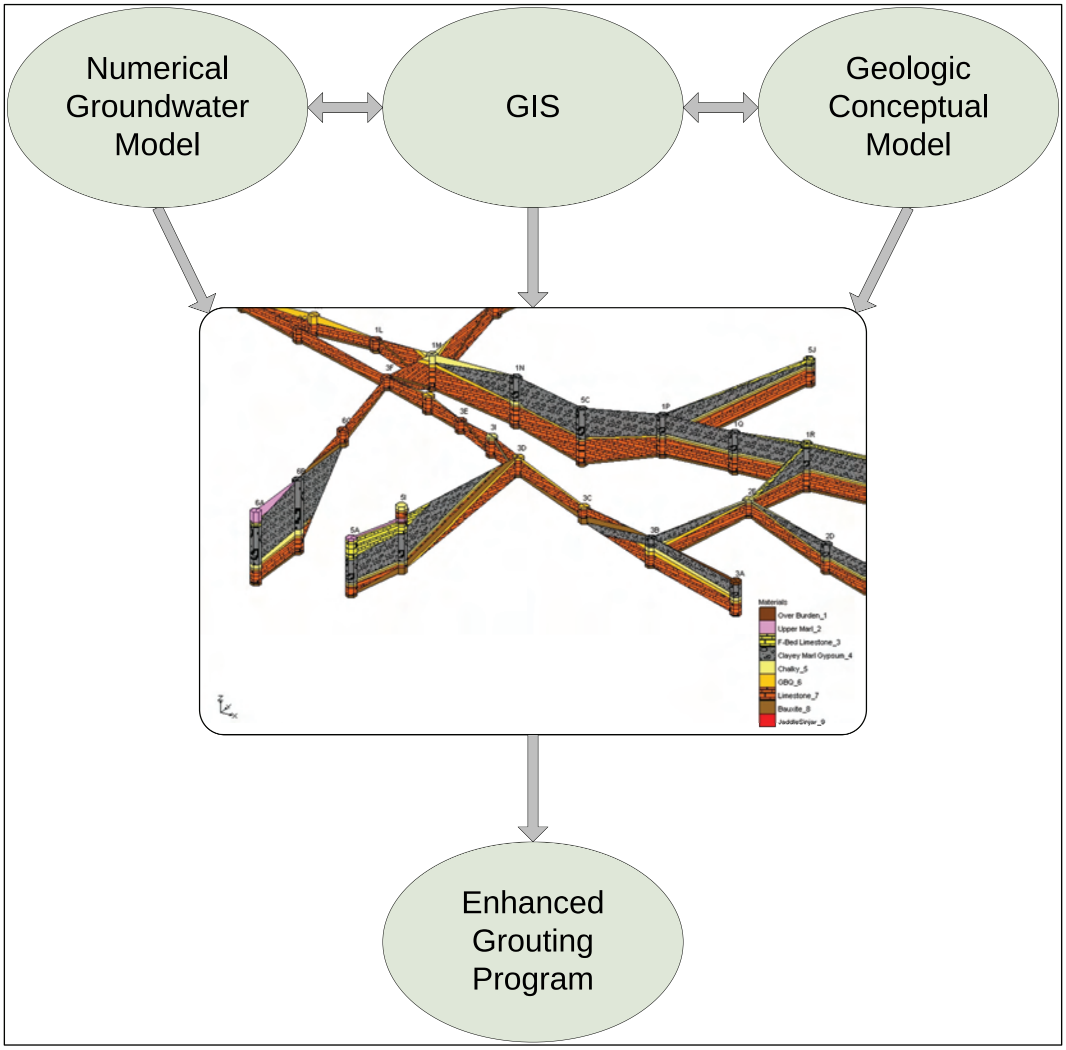

Figure 6. Intersecting cross sections generated from a working draft version (Sep 2006) of the ERDC geologic conceptual model, also indicating how the ERDC project supports the Enhanced Grouting Program. (The working draft wasbased on the simplified stratigraphy shown in Figure 5.)

adjoining areas upstream (under the water), downstream, and on both abutments. It extends from the anticline that forms the west abutment of the dam, and eastward across the dam to include a larger area of the east abutment and SD-5, a recent sinkhole located in the residential area. (Information about SD-5 was provided to the ERDC team by Abdulkhalik Ayoub, manager of Mosul Dam, during the September 2006 workshop.) All of the usable borehole logs were on the east (left) abutment, near the upstream end of the main spillway. To the north, the model extends just beyond the upstream face of the dam embankment. Downstream, the model extends beyond known surface expressions of seepage and other surface-drainage features. Figure 3 shows the 2-D (surface) footprint of the model.

5 Geologic Complexity

During the Data Exchange Workshop in September 2006, Ayoub and his staff provided detailed information about the geologic units in the abutments and foundation of the dam, including their official cross section of the geology through the long-axis of the dam. In workshop discussions, it became clear that the 3-D conceptual model being developed by the ERDC should include the level of detail indicated on the official cross section.

Annual reports of grouting over the past several years showed large and rapid changes in grout-curtain efficiency (described in Annual Reports of Dam Operations provided by Ayoub or included in the LOD). That is, formation permeability or effectiveness of the grout curtain at a certain location can change quickly, in weeks to months rather than the centuries to millennia expected in less dramatic geologic processes. These changes and other published and unpublished data indicate vertical and lateral changes with time on a fairly small scale (meters or submeter) within a single rock unit. The consensus of the September workshop participants was that the nine-unit simplified stratigraphy that had been used in 1984 hydrogeologic studies was inadequate for understanding the ongoing subsurface water movement, and for supporting the planned transition to an Enhanced Grouting Program.

To increase the usefulness of the model as a dam-management tool, the ERDC PDT deemed it necessary to include all of the geologic detail made available by the Mosul Dam staff, and to increase the level of complexity of the stratigraphy and structure in GMS. Like the LOD, the additional data were not in exportable data sets and were not digital. To generate files with the required details, the team gathered lithologic descriptions of each detailed unit from the annotations on cross sections, from boring logs, and from other sources with exacting lithologic descriptions. Distinctive geologic units called marker beds were identified in each data set, and correlated across the area of the model. The marker beds defined the total thickness of the stratigraphic column to the depth of investigation during the 1980s, and delineated changes in thickness of identifiable vertical segments of that column. After critical units were defined, the team used the original hydrogeologic study (Vol 13, LOD) to match stratigraphic units broadly to permeability values. The 3-D detailed model includes a

total of 43 distinct stratigraphic units. Appropriate permeability values were assigned to these 43 units based on best geologic judgment, bracketed by the high and low values from the original nine-unit simplified stratigraphy. Intermediate values were interpolated using information from lithologic and mineralogic descriptions.

After entering the data for boreholes and generated boreholes for the complex stratigraphy into the GMS software, the team used best geologic judgment to correct discrepancies, anomalies, and mismatched stratigraphy that occurred at intersections of the various cross sections. A multi-panel diagram of cross sections with complex stratigraphy, at an intermediate stage of resolution of discrepancies, is shown as Figure 7.

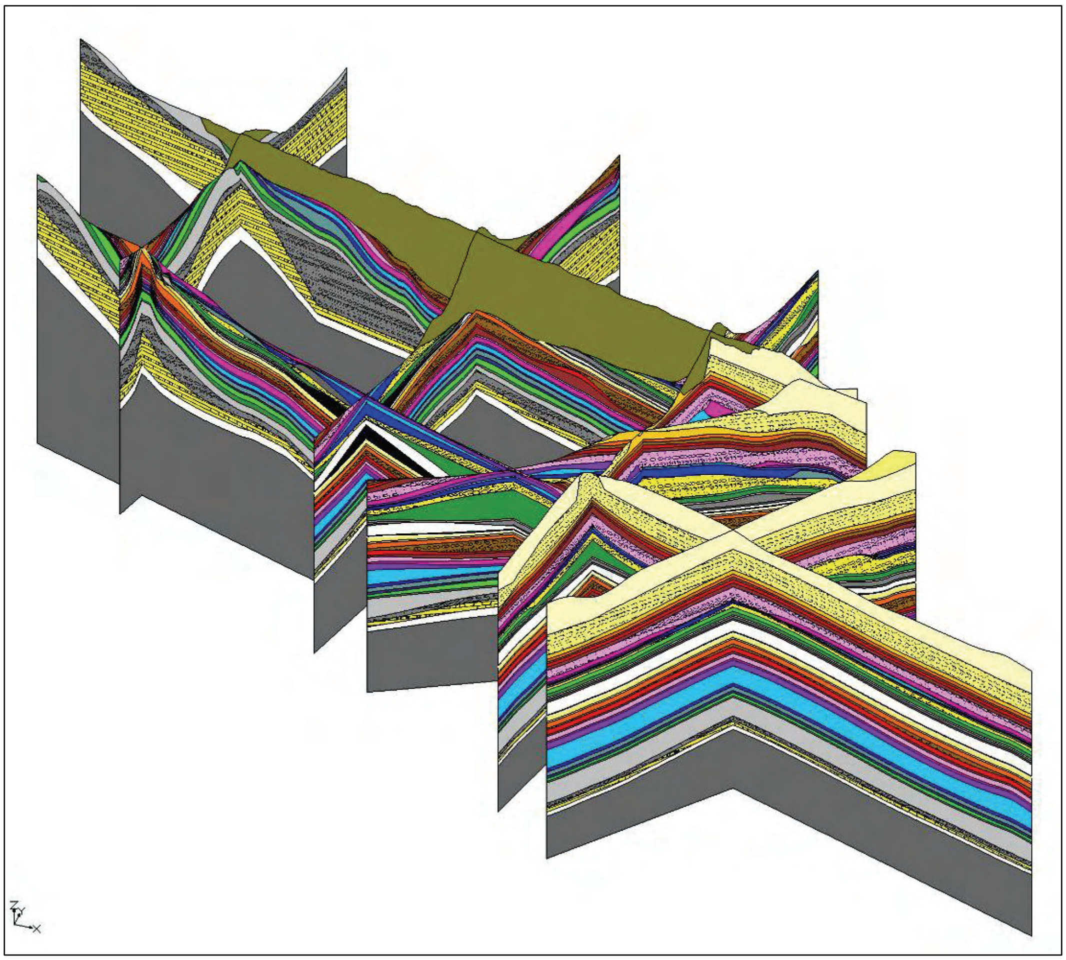

Figure 7. Intersecting cross sections from intermediate version of ERDC geologic conceptual model, showing complex stratigraphy and partial resolution of discrepancies in stratigraphy at intersections of the geologic panels from generated boreholes.

6 Using the Model

The 3-D model is a tool that allows dam staff or any other model user to view the spatial distribution of geologic units in the subsurface, at any depth and in any orientation. The user can create geologic cross sections at any spatial location and orientation within the footprint of the model. The geologic units also can be viewed in 3-D fashion, both individually or with any user-defined grouping. Figure 8 is a 2-D representation of a view of the 3-D model, looking toward the downstream face of the dam and a broad expanse of the east abutment from the southwest.

These options provide the ability to view and interpret the geology in two and three dimensions, and relate any other geospatial data to geology. They enable identification of layers or zones in the foundation with specific geomechanical characteristics or geotechnical properties. As an example, if the locations and depths of zones of high grout-take are known, these zones can be placed in their geologic context to reveal patterns and associations between high grout-take and certain geologic layers or features. The model can generate planes of data at any depth, such that any borehole drilled for grouting or instrumentation can be placed in a known geologic unit, to reveal patterns that could provide predictive capability for movement of dissolution zones. Figure 9 shows a horizontal section through the model at 227 m above sea level. It reveals the geologic complexity encountered at the base of the grouting gallery, attributable to differences in dip of the geologic units at different locations in the subsurface.

Although data for depth and location of grouting were not provided to the ERDC PDT, these data are available to the Mosul Dam staff, and they could be incorporated into the model. With the geologic data now in digital format, almost any digital data set deemed important in the future can be added to create predictive capability. Delineation of such features will be essential in conducting assessments of the stability of the dam and appurtenant structures, including performance under dynamic (seismic) loading.

Figure 10 is another view of a portion of the 3-D model, in which the difference in geologic structure of the two abutments is visible. A truncated portion of the Butmah anticline is exposed on the west (right) abutment,

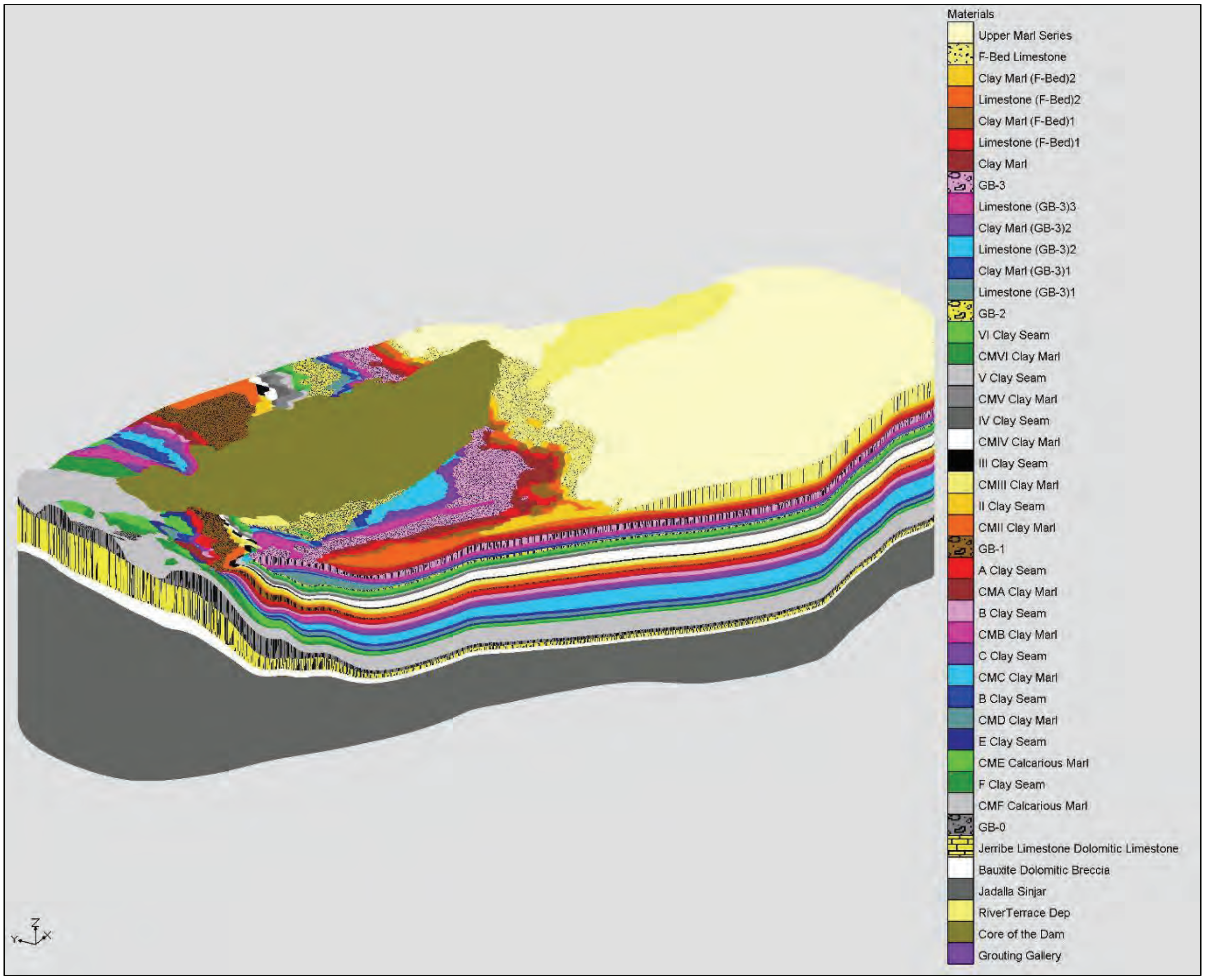

Figure 8. Two-dimensional projection of an oblique view of the 3-D conceptual model, looking upstream from the southwest toward the downstream face of the dam. (Broad yellow area is surface expression of near-flat-lying geologic units on the east abutment, contrasting to complex exposed geology of steeply dipping units under the dam and reservoir, and on the west abutment.)

where beds dip steeply in the subsurface. In the east (left) abutment, beds dip gently to the southeast, and appear nearly flat-lying in this particular view. Recent imagery is draped over the surface of the model, showing the dam and features of the west abutment.

The three-dimensional nature of the model, along with the ability to rotate, view, and create cross sections of the model, significantly adds to the understanding of the subsurface lithology beneath Mosul Dam and the

relevant processes that affect the behavior of the dam and its foundation under operating conditions.

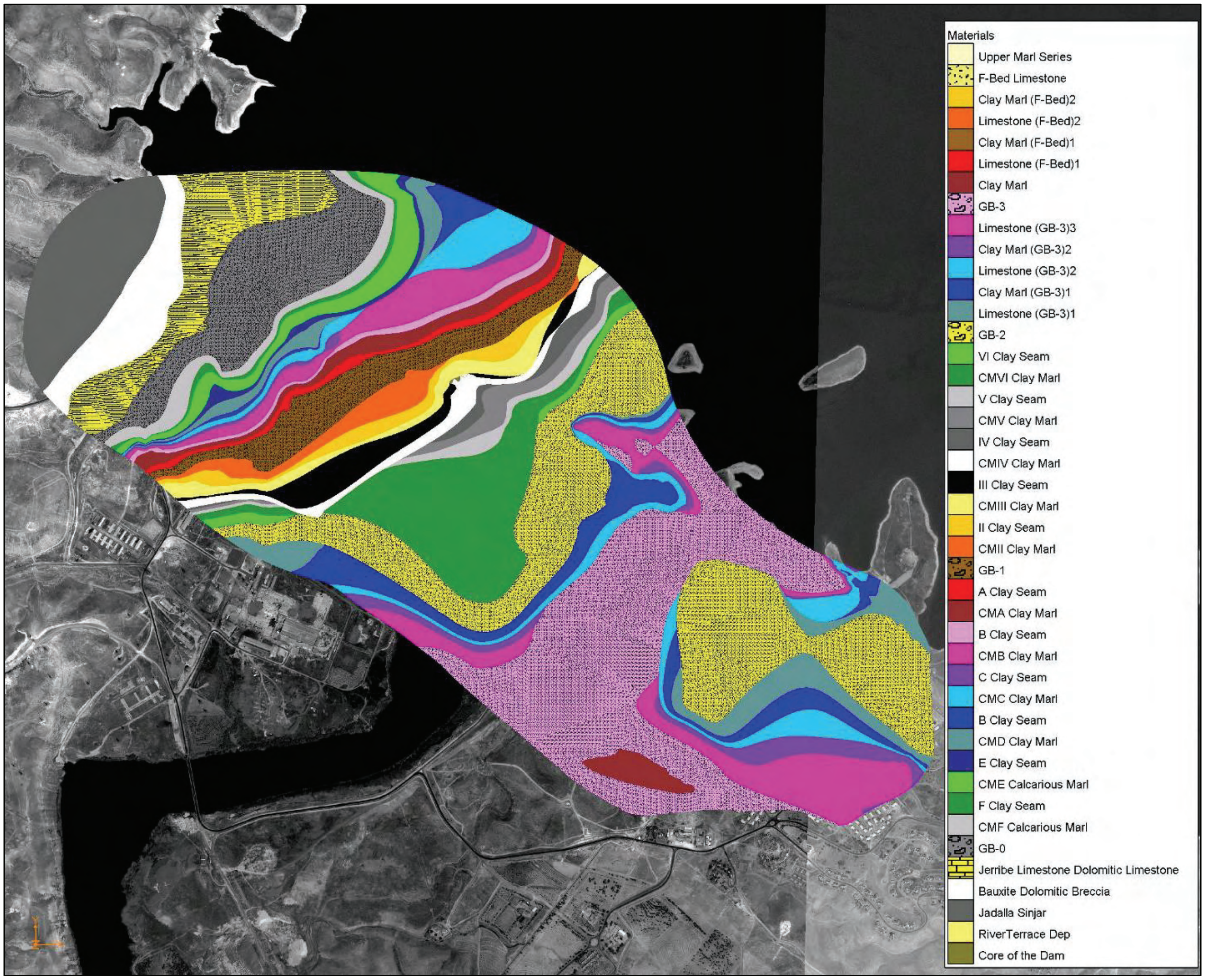

Figure 9. Horizontal "cut" through the geologic conceptual model at 227 m above sea level. (This is >100 m lower than the crest of the dam and just below the lowest part of the grouting gallery, illustrating the geologic complexity encountered in grouting operations.)

However, not all aspects of the conceptual model can be represented in the 3-D visualization tool. The understanding of changes through time could not be incorporated, because the geologic data available represented only 1980s conditions. The sections of the dam foundation and abutments that had high permeability values and Lugeon values (a type of permeability measurement used in grouting) in the 1980s are different from the focus areas of maintenance grouting since 2002. Table 1 shows locations of

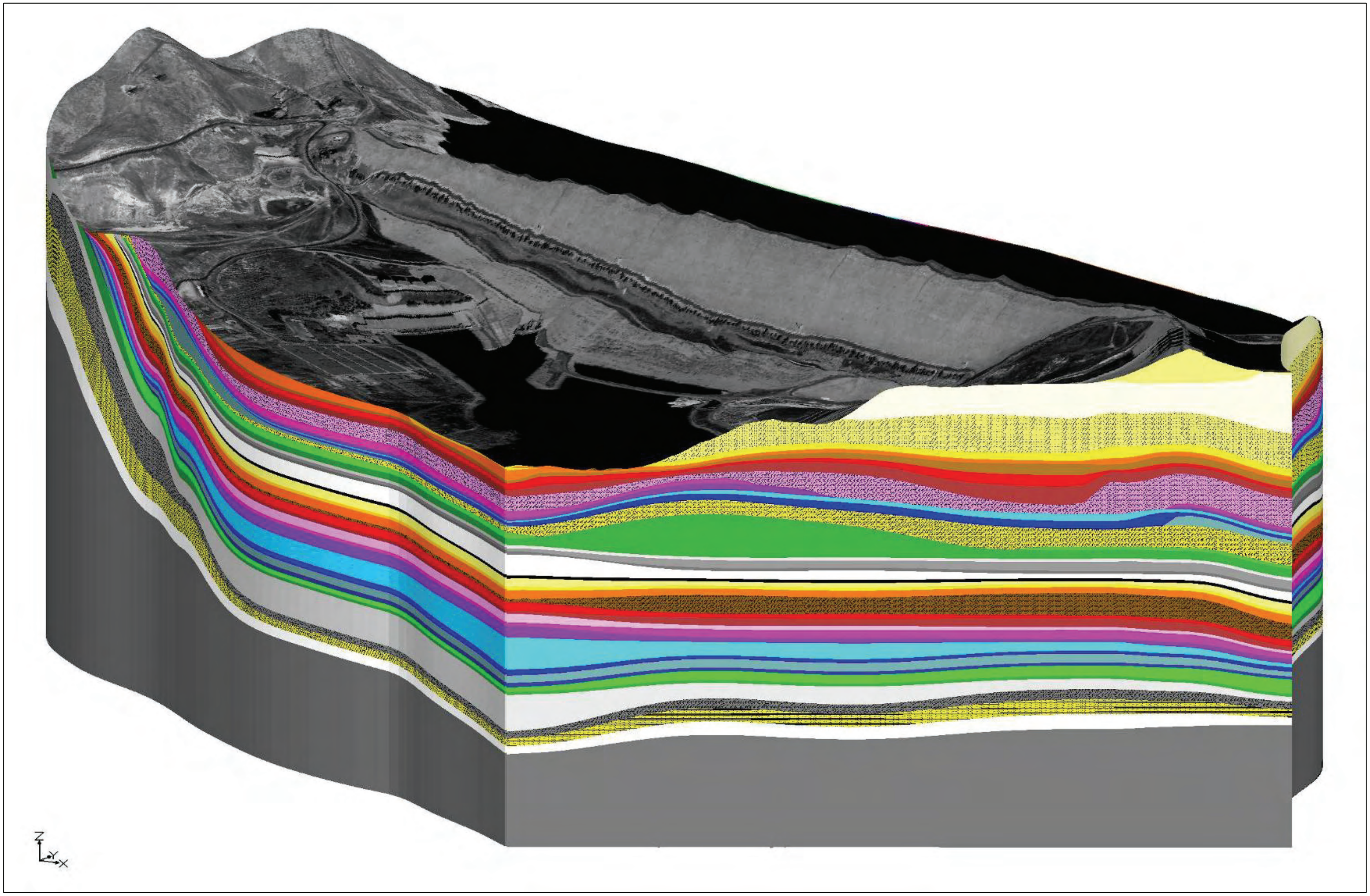

Figure 10. Two-dimensional projection of an oblique view of the 3-D conceptual model, with the southeast portion of the model cut away, looking upstream from the southeast toward the downstream face of the dam, with imagery draped over the surface of the model. (This view shows stark contrast in dip of the geologic units, with steep dips on the south flank of the anticline forming the hills to the west.)

Table 1. Locations (by section number, Mosul Dam) of grouting operations since 2002.

Grouting Locations 2002 through 2006

Dam Section	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115
2002		X		X		X		X		X	X	X		X	X	X		X						X		X			X	X	X	X	X	X	X	X	X	X													
2003				X													X		X	X			X						X								X	X	X	X	X	X	X	X	X	X	X				
2004					X				X				X		X	X		X			X	X	X		X		X	X																	X	X	X				
2005/2006					X		X	X			X	X			X	X	X	X	X	X	X			X																											
																																						O	O	O	O	Power Tunnels									
																						Active Channel																												
																Terrace and Channel Area																																			
	Grouting in GB-0 @ elevation of + 160 m.a.s.l.																																																		
	Dam crest 340 m.a.s.l.																																																		
	Pool max 330 m.a.s.l.																																																		

Source: Summarized from Annual Reports by the Mosul Dam staff). Section 115 adjoins the west (right) abutment; section 65 is west of the upstream end of the main spillway, near where the dam adjoins the east abutment. The table does not include information about open-air grouting on the east abutment (i.e., section numbers lower than 65.

recent grouting, derived from information in Annual Reports by the Mosul Dam staff.

Geologic exploration and analyses documented in the LOD had been performed in the 1980s, and the only permeability values included in the LOD had been measured in the 1980s. The geologic information available to the ERDC for building the model represented baseline conditions when the dam was built. Data for grouting—such as amount of grout placed at a fixed location and depth on a given day—were not provided as part of the data for model development.

In an area where dissolution of geologic material is a dominant and rapid process, the geologic details change quickly. Paper records for grout-curtain efficiency show that formation permeability or effectiveness of the grout curtain at a certain location can change in days to months rather than in centuries to millennia, as is expected in less dramatic geologic processes. Thus, the geologic and hydrogeologic models define conditions that existed in the 1980s. While this is an adequate representation of the regional geology and the general geologic structure that impacts dam performance, the model does not capture local changes caused by continued dissolution, formation of new pathways for fluid movement, or localized changes in permeability.

Without historic and recent data for such critical parameters as grout-take and chemical composition of seepage water, the ERDC PDT could not build visualization options showing changes in the subsurface as dissolution has progressed during the past 20+ years. Now that the baseline is defined and the data are digital, any appropriate digital and positional data could be incorporated into the model in the future, to track changes with time. Geochemical data, for seepage rates and water chemistry, would be especially useful for tracking the movement of the dissolution front and for predicting future problem zones.

7 Coordination with Gannett Fleming

From the outset of the project, the purposes of model development included providing the ability to visualize in three dimensions the structure, rock type, previous grout-takes, and parameters that control groundwater seepage, to assist in guiding the Enhanced Grouting Program to reduce major flows passing through the dam foundation or abutments. Further, the model was intended to enable model users to review and visualize local geology of the dam site where enhanced grouting will take place. Although the ERDC team did not have quantitative data for previous grout-takes, the team was able to accomplish these purposes, by transforming scores of historic paper documents and non-georeferenced pdf files into a 3-D geologic conceptual model in a software platform that is compatible with many other geospatial data formats.

To maximize the benefit of this effort, the ERDC team transitioned the 3-D geologic conceptual model of Mosul Dam to Gannett Fleming, Inc., for use in their application of IntelliGrout® in the Enhanced Grouting Program. The IntelliGrout® system is a comprehensive integration of data collection, real-time data display, database functions, real-time analytical capabilities, and computer-aided design to manage large-scale seepage-control and other grouting projects. Gannett Fleming, Inc., working in partnership with Advanced Construction Techniques, Ltd., developed IntelliGrout® for managing and accomplishing seepage control and stabilization of large earthen and concrete dams, and reconstruction of underground structures such as subways, tunnels, railway, water supply aqueducts, mines, and penstocks.

The software for IntelliGrout® requires site-specific geologic information in extraordinary detail. The geologic detail allows quantitative design of grouting operations so that the intensity of grouting is consistent with design assumptions. Grouting-hole orientation and depth are selected consistent with site geology, which also controls the maximum safe pressure for grouting. Data acquisition and data recording are computer-monitored by experienced and informed engineers and geologists, and adjustments of the grouting design, grouting mixtures, and grouting pressures are based on measured responses within the context of site geology. This interactive use of geology provides an electronic link between

digital data sets and eliminates sorting through paper logs, photographs, lab test results, etc., to interpret conditions. The ERDC 3-D conceptual geologic model of the Mosul Dam site provided the only available georeferenced data set to meet the site-specific data requirements of IntelliGrout®.

8 Technology Transfer

The ERDC team transitioned the 3-D conceptual model and numerical hydrogeologic model, along with other tools, to members of the Mosul Dam staff and other scientists selected by the Ministry of Water Resources through a hands-on workshop held in Ankara, Turkey, during 2 weeks in April 2007. The workshop included detailed information about the ERDC team's understanding of the regional and local geologic settings and their engineering implications, to ensure that workshop participants were comfortable with the level of knowledge behind, and detail built into, the 3-D model.

The principal objective of the workshop was to prepare the selected trainees to understand, apply, modify, and update the modeling tools developed by ERDC for Mosul Dam. To achieve that end, the training included exposure to and training in the following technical areas:

- Regional geologic setting for Mosul Dam
- Mosul Dam site geology
- Geochemistry of Mosul Dam
- ERDC Geologic Conceptual Model for Mosul Dam, and the logic path that led to its development
- ArcGIS® Geographic Information System (GIS) applications for Mosul Dam
- Structure and use of certain options in the Groundwater Modeling System (GMS)
- MODFLOW modeling
- ERDC Hydrogeologic Flow Model for Mosul Dam

Most of the workshop time was devoted to instruction and hands-on experience with the project GIS, as well as the 3-D conceptual model and numerical hydrogeologic model in GMS. One additional topic was acquisition and use of GPS data, to plan ahead for incorporation of new digital and georeferenced data files into the models.

All of these topics and activities were designed to empower the Mosul Dam staff to use and update the models during their transition from 1980s grouting methods and technologies to the Enhanced Grouting Program

based on IntelliGrout®. A summary of the April 2007 workshop is included as an appendix to this report.

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Appendix A: Summary of Model Technical Training Workshop, Ankara, Turkey, 15–26 April 2007

Introduction

The U.S. Army Engineer Research and Development Center (ERDC) has developed geologic conceptual modeling tools and a hydrogeologic model for Mosul Dam, Iraq in support of the enhanced grouting program planned for Mosul Dam. The culmination of this modeling effort was for ERDC to provide a comprehensive training opportunity for selected representatives from Mosul Dam and the Iraq Ministry of Water Resources (MWR) such that those representatives would be trained in all facets of the model.

Training objectives

The basic objectives of the training were to prepare the selected MWR trainees to understand, apply, modify and update the modeling tools developed by ERDC for Mosul Dam. To achieve that end, the training included exposure to and training in the following technical areas:

- Regional geologic setting for Mosul Dam
- Mosul Dam site geology
- Geochemistry of Mosul Dam
- ERDC Geologic Conceptual Model for Mosul Dam, and the logic path that led to its development
- ArcGIS Geographic Information System (GIS) Applications for Mosul Dam
- Groundwater Modeling System (GMS)
- MODFLOW Modeling
- ERDC Hydrogeologic Flow Model for Mosul Dam

Trainees

To fully benefit from the training program provided by ERDC, the trainees needed to possess a minimum set of qualifications and/or background experience prior to the training. The following is a summary of the recommended selection criteria:

- Adequate fluency in conversational and written English to understand course instruction, written materials and presentations.
- University degree, or equivalent, in geology, hydrogeology, hydraulic engineering, geotechnical engineering, or geochemistry. Other related educational background may be sufficient if supplemented by extensive experience in geology, groundwater hydrology, dam safety and operations or geotechnical grouting.
- Working knowledge of Microsoft Windows computer applications.
- Working knowledge of geographic information systems (GIS) or computer aided design (CAD) tools.
- Background and/or knowledge in the following topics is highly desirable:
- Transport processes
- Numerical modeling
- Mosul Dam geology / stratigraphy
- Mosul Dam grouting operations
- Mosul Dam instrumentation data

Following are the trainees who participated in the workshop:

- Mr. Ali Muhammed Jawad Nsayf, Ministry of Water Resources
- Ms. Manahil D. Sulayman, Mosul Dam
- Dr. Najwan T. Shareef, Mosul University
- Mr. Hussin H. Ahmed, Mosul Dam
- Mr. Mohsan Hassan Yiakob, Mosul Dam
- Mrs. Rafia A. Kasim, Mosul Dam

ERDC staff

The following staff from the ERDC planned the workshop, prepared presentation materials and the training notebook, and were present to share technical information in the workshop: Dr. Mark Jourdan, Program Manager for the Mosul Dam Project; Dr. Lillian Wakeley, geologist who

was responsible for the development of the conceptual geologic model; Mr. Cary Talbot, developer of the hydrogeologic model for Mosul Dam; and Mr. Seth Broadfoot, integrator of all the data into a GIS, making it functional for the conceptual geologic model and the hydrogeologic model.

Key findings

The workshop events are described, on a daily basis in Attachment A. The Workshop Outline is provided in Attachment B.

Following are some of the key findings and lessons learned by both the trainees and the instructors:

- Dr. Najwan observed that the objectives were very clear at the end of the first afternoon session.
- Mr. Ali observed that they really need a 3-D geochemical model so they can predict where the dissolution will move next.
- Mosul Dam (MD) staff said the four sets of subsidence readings on plots prepared by the ERDC are the only long-term data sets for subsidence.
- MD staff said the gallery patches visible in Dec 06 photographs are from construction (not settlement). They described a strong smell of sulfur in Sections 65 to 77, exiting from piezometer holes. Workers are reluctant to work in those sections.
- John Barron, a contractor to the USACE Gulf Region Division (GRD) visited the class, expressed that he was impressed with the focus of the students and their dedication to learning the tech transfer material from the ERDC.
- The students stated that they want 3-D geochemical data incorporated into the model so they know from where the most material is dissolving.
- The ERDC learned about the current drilling program on the east abutment, and the MD staff members requested that the ERDC incorporate new geologic data from these geologic borings into the conceptual model.
- The students requested another workshop after they have IntelliGrout (IG) software and have been using IG and our model for awhile. They requested additional tools to be able to compare old instrumentation data to data they get from instrumentation after they start using IG.

Conclusions

The workshop, held on 15-26 April in Ankara, Turkey, was considered a very successful technology transfer. The ERDC staff were able to meet, interact with, and learn from some of the key personnel in the Mosul Dam staff and the Ministry of Water Resources. Attachment C includes several pictures from the Workshop. The attendees worked very hard the entire time, made many suggestions and requests for additional ERDC efforts, and left with a very good understanding of the hydrogeologic processes occurring at the dam, as well as the ability to model those processes. The attendees stated that they believe an additional training session, once the IntelliGrout equipment is in place, would be very beneficial in understanding the enhanced grouting program and the effects of this program on the safety of Mosul Dam.

Attachment A: Daily Notes on Model Technical Training Workshop

Day 1: 15 April 2007, 1300 to 1630

The ERDC Team introduced and presented an overview of the ERDC project, and summary of topics and purposes of each section: geology and its engineering implications; introduction to using GIS; the development of the GMS-based conceptual model; the development and use of the hydrogeologic model using GMS; and use of GPS units. The U.S. and Iraqi participants introduced themselves and shared information about their work and their families.

Principal objectives of the geology section are to explain the information we used and the logic path we followed to understand the site, so the MD staff and others will trust the model; and to begin the transition from thinking in 2-D to thinking in 3-D and 4-D (with time).

Objectives of section on using GIS are to introduce the power of the tool and demonstrate its use in managing very large data sets, such as the data for Mosul Dam; and to practice software skills essential for using GMS. Explanation of the process of going from paper data to GIS to conceptual model is intended to continue building trust in the model by showing how we got from data in their accustomed format to data in GMS.

The section on development and use of the model in GMS is the centerpiece of this technology transfer effort, transitioning the best possible tool to MD and MWR staff for their own use in managing and maintaining their dam. Providing GPS units and training them to use GPS is intended to strengthen use of data with a high level of positional accuracy, and thus reinforce use of the models and the new EGP equipment and software.

At the request of the students, we continued beyond the introduction and overview, and began with information about formation of the Arabian Plate and geologic factors that established the depositional environment of northern Iraq.

Dr. Najwan observed that the objectives were very clear at the end of the first afternoon session.

Day 2: 16 April 2007, 0800 to 1745

Presentations and discussions about geology of the MD site continued with establishing the depositional environment for the evaporate units at the site and explaining their extreme variability laterally and vertically. We continued with information on water chemistry, dissolution rates, and the relationship between reservoir level and dissolution of gypsum as indicated by composition and amount of seep water. Mr. Ali assisted in explaining some of the geochemistry data.

Among the highlights of the geologic material were the ERDC cross section enhanced by kriging to show changes in formation permeability at the time of construction; and discussion of current trends in grouting toward the east abutment. The ERDC team showed how grouting in one section moves the problem to an adjacent section subsequently, and predicted where they needed to grout in 2007 based on our interpretation of grouting trends in 2002 through 2006. Mr. Mohsan confirmed that they grouted in the sections we predicted. Dr. Najwan observed that the kriging section did not agree with the recent eastward grouting trend, which helped us reveal the changes in the subsurface with time, thus adding the fourth dimension to the discussion. The water chemistry and grouting data together helped show that human activity (impoundment of the reservoir, fluctuation of the water level) has increased the rate of dissolution in the foundation and east abutment. Mr. Ali observed that they really need a 3-D geochemical model so they can predict where the dissolution will move next.

There was extensive discussion to clarify many technical points, in which Dr. Najwan and Mr. Ali acted as translators when needed to assure understanding throughout the group. They continued to serve as translators spontaneously as needed throughout the workshop.

Monday afternoon continued with each student setting up a computer provided by the ERDC and ERDC beginning the introduction to GIS. Focus of first GIS sessions was on introducing GIS tools that were used by the ERDC to develop the database that led to the geologic conceptual model. At the close of the session the students took the computers to their rooms to continue working with the GIS each was building. Note: The students took the computers to their rooms every evening during the workshop weeks, to continue working.

Housekeeping issues: The ERDC team requested additional supplies and data to be FedExed from Vicksburg. Dr. Jourdan assisted the students with business issues related to hotel bills.

Day 3: 17 April 2007, 0800 to 1745

ERDC presented information on the engineering significance of grouting, RQD, rock strength, piezometer readings, TDS, and subsidence data. Mosul Dam staff said the four sets of subsidence readings on our plots are the only long-term data sets for subsidence. Curves suggest uplift some years. ERDC will check into possible causes (data error, grouting pressure, expansion of anhydrite; uplift from pore pressure seems most likely) if ERDC involvement in the project continues.

MD staff said the gallery patches visible in Dec 06 photographs are from construction (not settlement). They described a strong smell of sulfur in Sections 65 to 77, exiting from piezometer holes. Workers are reluctant to work in those sections, and their hands turn black when they touch equipment that has been in the holes.

The group discussed evidence that no more large cavities are forming under the main dam, because grouting keeps openings small and moving from place to place rather than dissolving in a single opening for a long time. All evidence shows that the dissolution front is moving to the east.

Some of the GIS concepts discussed early in the workshop were as follows: basics of ArcGIS, opening and adding data in ArcMap, types of spatial data, a brief overview of projections, labeling and symbolizing data, and working with existing data. Every concept was discussed, and exercises built around that concept were completed.

The MD staff asked many thought-provoking questions related to spatial data and GIS. Most of their questions were directly related to the Mosul Dam model while some were applicable to GIS related to their other current projects at Mosul Dam. Their questions directly related to the Mosul Dam model covered subjects such as absolute X and Y, more in-depth spatial referencing and projection questions, and georeferencing for raster and vector data. The questions were addressed and often an ancillary exercise was created to help in the explanation of the concept.

The Mosul staff's general questions about GIS use in their other projects were addressed as time permitted. A few examples of these questions are: how to model flow (specifically in ArcGIS), where to purchase or download specific types of data, and how to use terrain or elevation data? If a solution was available it was delivered to the Mosul dam staff through tutorials and other exercises.

Day 4: 18 April 2007, 0800 to 1745

ERDC began additional instruction in GIS and continuing hands-on computer activities for workshop participants. Topics included creation of new data, editing data, working with images, saving data, supported file formats, and exporting data to formats usable by other software specifically GMS.

Continuing Wednesday afternoon, the ERDC instructor demonstrated additional GIS concepts. The trainees then worked through various exercises designed by the ERDC to instill a better understanding of the concepts and the many steps involved in development of the conceptual model.

Day 5: 19 April 2007, 0800 to 1700 with individual instruction continuing until 1830

The ERDC team completed GIS instruction with additional hands-on computer-based activities. We then initiated GMS instruction and hands-on exercises. Presentations covered history of development of GMS, development of conceptual models with examples of simple conceptual models, selecting model boundary conditions, 2-D vs. 3-D and steady state vs. transient flow, model calibration, and using models for prediction.

ERDC transferred photos of learning sessions to Manahil. John Barron from GRD visited the class, expressed that he was impressed with the focus of the students and their dedication to learning the tech transfer material from the ERDC. ERDC scientists remained after the session ended to provide individual instruction in details of GIS applications. Seth provided information about how to import images from Google Earth or other sources, and how to georeference the images for import into a GIS.

Day 6: 20 April (no classes–Sabbath for trainees)

Day 7: 21 April 2007, 0800 to 1800

GMS instruction, discussion, and hands-on exercises continued. Exercises focused on setting up a coordinate system, defining a base map, importing images, constructing a conceptual model, and coverages.

Day 8: 22 April 2007, 1400 to 1800

The ERDC team continued GMS instruction, tutorials, and hands-on exercises. Subjects covered included 2D and 3D geostatistics, using borehole data and cross sections the first part of MODFLOW.

Day 9: 23 April 2007, 0800 to 1730

The ERDC team continued GMS instruction with MODFLOW. Exercises defined layer data, and introduced MODFLOW coverage setup using real dataset from east Texas. A tutorial on using MODPATH included applications of particle tracking, and input and output options.

Day 10: 24 April 2007, 0800 to 1745

The workshop continued with GMS hands-on work using dataset from east Texas. Tutorials and exercises covered observation coverage, point and flux observations, and calibration statistics. ERDC answered more questions about resolution of files relative to printing and plotting.

A spontaneous 30-minute discussion addressed capabilities and limitations of the ERDC model. The four engineers from Mosul Dam asked about things they would like the model to do. Much of what they had pictured is either not possible with any model, or is subject matter that probably will be accomplished with IntelliGrout software. For example, they wanted to know if the model could tell them the depth where there is a break in a piezometer wire (no). They wanted to know if it could keep track of grout-take data, depth data, piezometer data, etc in real time (IntelliGrout [IG], according to our understanding of the Gannett Fleming system). We tried to explain what we understand is the purpose of IG software. They wanted us to add all the grout-take-with-depth to the model. We told them we had intended to put grouting data in the model but the ERDC did not receive the data. They want to send the data to us and have us add it now, and then change flow parameters and etc. We told

them our contract is ending, and encouraged them to tell Mr. Ayoub that they need additional interaction with the ERDC to use all the new tools effectively.

They repeated that they want 3-D geochemical data incorporated into the model so they know from where the most material is dissolving. We assured them that neither IG software nor our model will replace the experienced people working at the dam. IG and the ERDC model are just tools that can only be used wisely if their brains are in the loop. They concluded that the model and the software will not solve the problem, but will give them tools to do their jobs better. They requested another workshop after they have IG software and have been using IG and our model for awhile. They requested additional tools to be able to compare old instrumentation data to data they get from instrumentation after they start using IntelliGrout. They want someone to fit all these things together, along with the new materials, equipment, etc., so that all the new physical and digital tools become a usable system instead of separate items. Their description sounded like they know they need an Implementation Plan.

ERDC introduced the geologic conceptual model of Mosul Dam and explained how it was built using GMS software. Students launched a discussion about the depth of the grout curtain and range of depth of recent grouting operations (120m). Maximum depth of grout curtain is different for different locations along the grouting gallery, as we would expect from movement of the dissolution front and dip of the beds.

In another discussion, Mr. Mohsan described the current activity of drilling four new boreholes to a depth of 100m below the surface, all on the east abutment. They have started drilling a hole in the village, and will continue to the west with the fourth borehole to be located near the spillway. They want the data from these boreholes to be incorporated into the geologic model, but do not expect to be able to enter those data on their own. They need to use the 3-D tools to do their jobs better, and do not have computer power adequate to be able to build large quantities of additional data into the model.

Housekeeping issues: After additional hands-on work with the Mosul Dam model, we ended the day with a review the requirements for completing a travel voucher, including a ppt presentation of a completed voucher.

Day 11: 25 April 2007, 0800 to 1730

Power was off in usual meeting room. Workshop was relocated to Sheraton Board Room.

The ERDC team and MD team discussed the concept of an Implementation or Integration Plan, and discussed potential requests for additional interaction and coordinated work. The two groups have formed a single team in our understanding of the technical challenges to dam safety, and the need to coordinate all separate parts of the hardware, software, tools and technologies being provided to the Ministry for use at Mosul Dam.

Work continued with the Mosul Dam model. Topics included cutting horizontal and vertical cross sections, using borehole data, different options for 2-D and 3-D viewing of data, and various software options needed to use the model. Exercises covered hands-on versions of many visualization choices and tools.

ERDC team arranged with Sheraton management to use the tennis court for GPS training planned for Day 12. The tennis court is a safe location with lines on the ground for positional accuracy, and is included in available coverage (Google Earth and other). ERDC confirmed essential satellite coverage for a GPS lesson on the court, although tall buildings surrounding the court distort the data. The GPS signals are being affected by multipath issues, where the radio signals reflect off the surrounding buildings (the same thing would happen in a steep-walled canyon). These delayed signals cause the shape of the tennis court to be distorted, but it can be used to teach techniques.

Day 12: 26 April 2007, 0800 to 1630

The ERDC team answered specific questions of the trainees related to their evening work with the Mosul Dam model.

New material presented by the ERDC included concepts of GPS, how GPS works, how accuracy is determined, and summary of commercial data types. Hands-on GPS instruction covered finding satellites, directions and coordinates, and specific controls for the GPS units distributed. After explaining concepts of GPS coordinates and waypoints, the hands-on class moved to the Sheraton tennis court to find current position and acquire

positional data. Classroom activity resumed with downloading data from the unit and incorporating positional data from the GPS into a GIS.

ERDC team members presented certificates of completion for the workshop to the 6 trainees, and photographed the group with certificates. We also created new DVDs and CDs for all Iraqi participants that included photographs of the entire workshop taken by Talbot and Wakeley, including photos from the tennis court activities and certificate presentation; and including new instructional materials for GIS and GPS. We gave Manahil another copy of the teaching book and a DVD with all teaching files and photographs to take to Mr. Ayoub. All trainees departed with CDs and/or DVDs of instructional materials and photos, GPS units with cables and instructions, and one or more copies of the teaching notebook with printouts of all presentations. In addition, Hussin and Manahil received the large-format printed cross sections, maps, stratigraphic columns, and other materials we had brought from Vicksburg and used for discussion during the class.

Attachment B: Model Technical Training Workshop Outline

Day 1 (Sunday 15 April)

Time	Activity	Topic
15:00–16:00	Opening remarks	Introductions and overview of the project (Wakeley)
16:00–17:00	Lecture	Objectives of the workshop Questions?
17:00	Adjourn	More questions?

Day 2 (Monday 16 April)

Time	Activity	Topic
08:00–09:00	Exercise	Geologic Cross section East to West through the dam
0900–0915	Break	
09:15–09:45	Lecture	Geologic History of Northern Iraq (Wakeley) Plate tectonics Arabian Plate Movement Relate paleofacies to stratigraphic column
09:45–13:30	Business and lunch	Trip to Embassy, check cashing and other business issues (Jourdan)
13:30–14:30	Lecture	Geologic History of Northern Iraq continues Complexity in stratigraphy of dam foundation Sabkha depositional environment
14:30–14:45	Break	
14:45–15:30	Lecture	Geologic History of Northern Iraq continues Regional geomorphic zones Anticlines/geomorphic features Structural elements Regional strike and dip River geomorphology
15:30–16:30	Discussion	Summary of Day 1 and 2 Geology Questions?
16:30	Adjourn	More questions?

Day 3 (Tuesday 17 April)

Time	Activity	Topic
8:00–8:30	Discussion	Identify major geomorphic features before dam construction (All)
8:30–9:45	Lecture	Geologic processes of erosion (Wakeley) Processes of dissolution Limestone vs. gypsum Gypsum breccia and dissolution front Grouting in breccia
9:45–10:00	Break	
10:00–12:00	Lecture	Seepage Water chemistry and geochemistry Dissolution processes
12:00–13:00	Lunch	
13:00–15:00	Lecture	Geologic processes of erosion continue Formation and location of sinkholes Location of dissolution front Modeling the dissolution front Rock quality (RQD)
15:00–15:15	Break	
15:15–15:45	Discussion	RQD (determine from photos of cores) (All)
15:45–17:00	Lecture	Site Geology Discussion of official cross section Lugeon values Condition of rock before construction Grouting data Mass movement at surface Summary of Day 3 Geology

Day 4 (Wednesday 18 April)

Time	Activity	Topic
8:00–9:45	Lecture	Engineering implications (Wakeley) The geology of grouting East Abutment dissolution, RQD, sinkholes Piezometer data Settlement of gallery and dam crest Summary of Day 4 Geology
9:45–10:00	Break	
10:00–10:30	Discussion	Summary of path to conceptual model Questions?
10:30- 12:00		Introduce framework of computational model (Broadfoot) Assessment of GIS concepts
12:00–13:00	Lunch	
13:00–14:45		Introduction to ArcGIS ArcMap, ArcCatalog, ArcToolbox Types of data Brief overview of projections
15:00–15:15	Break	
15:15–16:00	Lecture	Adding, displaying and editing in ArcMap
16:00–17:00	Exercise	Adding, displaying and editing in ArcMap

Day 5 (Thursday 19 April)

Time	Activity	Topic
8:00–9:00	Workshop	Working with existing Mosul cross sections (Broadfoot) Extracting data from cross sections Defining geologic formations
9:00–10:00	Exercise	Derivation of geologic data from existing hard copy data
10:00–10:15	Break	
10:15–11:00	Lecture	X, Y data in ArcMap X, Y data into spreadsheet GMS format of spreadsheet
11:00–12:00	Exercise	Data for GMS from geologic borings
12:00–13:00	Lunch	
13:00–15:00	Workshop	Introduction to GMS (Broadfoot) Viewing boreholes in GMS
15:00–17:00	Exercise	Input of spreadsheet and text files into GMS Viewing and displaying borings in GMS

Day 6 (Friday 20 April)

Time	Activity	Topic

8:00–8:15	Lecture	Introduction (Talbot)
		    Introduction to GMS
		    History of development

8:15–9:00	Lecture	Groundwater Modeling Concepts
		    Conceptual Model Development
		    Selecting Boundary Conditions
		    2-D vs. 3-D
		    Steady State vs. Transient
		    Code Selection
		    Model Calibration
		    Prediction

9:00–10:00	Lecture	Getting Started on a Modeling Project
		    Setting up a coordinate system
		    Selecting Units
		    Defining a base map
		        Importing images
		        Importing CAD drawings
		    Constructing a conceptual model
		        Conceptual model objects
		        Coverages
		        Feature objects

10:00–11:00	Lecture	2-D Geostatistics
		    2-D Scatter point module
		    Text Import Wizard
		    Interpolation methods
		3-D Geostatistics
		    Brief intro and demo

11:00–12:00	Workshop	2-D Geostatistics Tutorial
12:00–13:00	Lunch	

13:00–14:00	Lecture	Site Characterization with Boreholes & Cross Sections
		    Borehole data
		    User-defined cross sections

14:00–14:45	Workshop	Cross Section Tutorial

14:45–15:45	Lecture	Site Characterization with Horizons
		    Horizons → Solids
		    Horizons → HUF

15:45–17:00	Workshop	Horizons Tutorial

Day 7 (Monday 23 April)

Time	Activity	Topic
8:00–9:00	Lecture	MODFLOW – Part I Overview Basic, BCF-LPF-HUF, Recharge, Well, Drain, Solver Packages Grid-based pre-processing Model Checker Launching MODFLOW Post-processing
9:00–10:00	Workshop	MODFLOW - Grid Approach Tutorial
10:00–11:00	Lecture	MODFLOW – Part II River Stream-Aquifer Interaction General Head Changing Head Boundary Horizontal Flow Barrier
11:00–11:30	Lecture	MODFLOW – Interpolating Layer Elevations Interpolation from scatter points
11:30–12:00	Workshop	Defining Layer Data
12:00–13:00	Lunch	
13:00–14:00	Lecture	MODFLOW Conceptual Model Approach Strategies MODFLOW Coverage Setup
14:00–15:00	Workshop	MODFLOW Conceptual Model Approach Tutorial
15:00–15:45	Lecture	MODPATH Applications of Particle Tracking Setting up the input Output Options
15:45–16:30	Workshop	MODPATH Tutorial

Day 8 (Tuesday 24 April)

Time	Activity	Topic
8:00–9:00	Lecture	Calibration Tools Importing Observation Well Data Calibration basics Observation coverage Point Observations Flux Observations Plotting calibration statistics
9:00–10:00	Workshop	Model Calibration Tutorial
10:00–12:00	Lecture	Introduction to Mosul Dam MODFLOW model Borehole & cross-section data Horizons Solid model Conceptual model MODFLOW finite difference grid
12:00–13:00	Lunch	
13:00–15:00	Lecture	Mosul Dam MODFLOW model (cont.) MODFLOW parameters Check simulation Running MODFLOW Post-processing MODFLOW run Defining grouting zones in model
15:00–16:30	Workshop	Mosul Dam Model Workshop

Day 9 (Wednesday 25 April)

Time	Activity	Topic
8:00–9:00	Lecture	Mosul Dam Model Scenarios
9:00–12:00	Workshop	Mosul Dam Model Workshop
12:00–13:00	Lunch	
13:00–16:00	Workshop	Mosul Dam Model Workshop
16:00–16:30	Lecture	Mosul Dam Model Discussion & Wrap-up

Day 10 (Thursday 26 April)

Time	Activity	Topic
8:00–9:00	Lecture	History of GPS (Broadfoot)
9:00–10:00	Lecture	How does GPS work, accuracy of GPS Introduction to WAAS & EGNOS
10:00–10:15	Break	
10:15–12:00	Workshop	Powering up, finding satellite, directions and coordinates GPS - buttons & main pages; battery; power; display; etc. Basic operation of the Garmin unit
12:00–13:00	Lunch	
13:00–15:00	Workshop	GPS setting up Position format Map datum north reference, etc.
15:00–16:30	Workshop	Finding position GPS coordinates Way points Mark a point Input manually Download data from the unit
16:30–17:00	Summary	Questions? (All)

Attachment C: Photographs from the Model Technical Training Workshop

Seth Broadfoot giving tips to Hussin, as Rafia (right) and Manahil work on lessons.

Ali helping other trainees.

Cary Talbot explaining the use of the GPS.

Trainees (with certificates) and ERDC staff. Front from left is Mrs. Rafia A. Kasim, Dr. Lillian Wakeley, Ms. Manahil D. Sulayman, Dr. Najwan T. Shareef; back row from left is Mr. Seth Broadfoot, Mr. Hussin H. Ahmed, Mr. Ali Muhammed Jawad Nsayf, Mr. Mohsan Hassan Yiakob, and Mr. Cary Talbot

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Accompanying CD provides input cross sections and borehole logs.

14. ABSTRACT
Mosul Dam, Iraq, was built in the 1980s on a foundation of soluble geologic materials. Because of the solubility of its foundation and abutments, maintenance grouting began immediately after construction and continues to the present. The U.S. Army is concerned about the stability of the dam, and about the potential military and political impacts that would accompany dam failure. At the request of the U.S. Army Corps of Engineers' Gulf Region Division, the U.S. Army Engineer Research and Development Center (ERDC) developed a three-dimensional (3-D) geologic conceptual model of the dam, as a tool to assist with improving dam safety and updating grouting operations. To develop the model, the ERDC project delivery team built a geographic information system based on recent imagery, coupled with paper maps and geologic cross sections from the 1980s with minimal and inconsistent positional accuracy. Historic geologic data were translated into digital files and georeferenced, then consolidated and refined into a consistent set of lithologic information that was entered into the U.S. Department of Defense Groundwater Modeling System (GMS), the U.S. Army's specialized tool for performing subsurface modeling studies.

(Continued)

15. SUBJECT TERMS

Dam safety	Geologic model	Hydrogeology	3-D modeling
Foundation grout	GIS	Iraq geology	
	Gypsum	Karst	

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
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14. ABSTRACT (Concluded).

Using the tools available in GMS, the ERDC team constructed a 3-D geologic model of the foundation and abutments comprising 43 unique geologic units. The 3-D nature of the model, along with the ability to rotate, view, and create cross sections, adds significantly to the understanding of the size, shape, and arrangement of rock units beneath Mosul Dam and the relevant processes that affect the safety of the dam and its foundation under operating conditions.